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CIRCULATION CHANGE AND EBB SHOAL DEVELOPMENT FOLLOWING RELOCATION OF MASON INLET, NORTH CAROLINA

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ABSTRACT: In March 2002, under the direction of the first author, a rapidly migrating inlet located in New Hanover County, North Carolina was relocated. The original entrance to Mason Inlet was closed, and the inlet was reopened approximately 850 m (2,800 ft) to the north. In addition, a 1,400-m (4,580 ft) long channel was dredged between the new inlet and the Atlantic Intracoastal Waterway (AIWW), and a sedimentation basin was constructed west of the new inlet entrance. Monitoring was initiated to determine if the downdrift beaches receive sediment from breakup of the abandoned ebb shoal and to assess development of the new ebb shoal, including natural sand bypassing. This paper examines ebb shoal development, inlet cross-section equilibration, beach response, and changes in the tidal prism and flow distribution through the primary two tidal channels connecting the new inlet with the AIWW following the inlet's relocation. Locational and cross-sectional stability of the entrance channel are also discussed.

INTRODUCTION

During the past 30 years, Mason Inlet has slowly migrated to the south. As a result, the north shoreline at Wrightsville Beach and the southern beaches at Figure Eight Island have experienced extensive sand losses and both islands require shore protection to protect their expansive developments (Fig. 1). Since 1985, the inlet's steady movement to the south has resulted in the loss of 670 m (2,200 ft) of shoreline at the north end of Wrightsville Beach. In 1997, this migration placed the inlet within 65 ft of the Shell Island Hotel Resort's 10-story north tower. In addition to the hotel, 38 single-family homes and three condominium developments were at risk of total loss if the inlet was to continue its southerly migration.

The "imminent threat" to the Shell Island Hotel resulted in the State of North Carolina granting a variance for a permit to construct a temporary 6 m (20 ft) high, 130 m (425ft) long geotextile revetment along the hotel's foundation to prevent further movement of the inlet in 1997 (Fig. 2). The State of North Carolina's prohibition of hardened structures is an outcome of a 1985 general statute that strictly prohibits construction of hardened erosion-control structures on the ocean shoreline, except for protection of roads and national monuments. This statute prohibited placement of a terminal training groin or similar structure to control the inlet's position, thereby requiring the affected property owners to develop a long-term solution without stabilizing structures. With the impending December 2001 deadline to remove the temporary revetment approaching, and an agreement by the stakeholder group's property owners to repay the County for the costs of implementing a long-term solution to the inlet problem, New Hanover County contracted with a coastal engineering firm to begin work.

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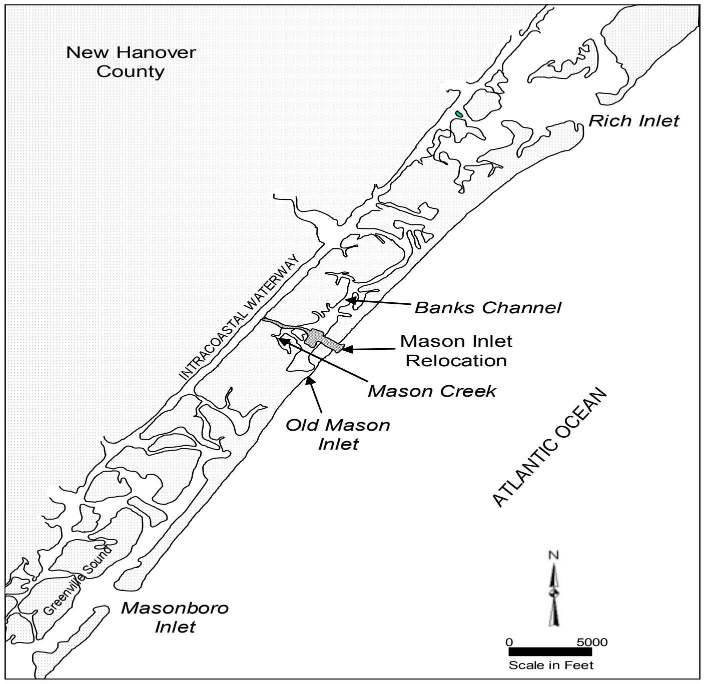

Fig. 1. Study site location map

Mason Inlet is a shallow tidal inlet with 1.2 m (3.8 ft) mean tidal range and 1.5 m (4.8 ft) mean spring tidal range, connecting the Atlantic Ocean and Banks Channel between Figure Eight Island and Wrightsville Beach, New Hanover County, North Carolina. The area between the AIWW and Mason Inlet is the Middle Sound Estuary that encompasses Banks Channel and Mason Creek tidal channels, numerous small tidal channels, and a broad area of wetland marsh. As evidenced in photographs from the 1960's and 1970's, Mason Creek was the primary tidal channel between the AIWW and Mason Inlet prior to development of Figure Eight Island. During that time, Mason Creek was nominally 1.8 m (6 ft) in depth, and relatively stable. Following deepening of Banks Channel to a depth of 3.7 m (12 ft) (NGVD), Mason Creek began to shoal. By 1999, bed elevations in Mason Creek were only -2 to +1 ft (NGVD), and the resulting tidal flows had shifted from Mason Creek to Banks Channel.

The inlets adjacent to Mason Inlet are the federally maintained, Masonboro Inlet located 8 km (5 miles) to the south and Rich Inlet located some 5.6 km (3.5 miles) to the north. The tidal flows and tidal prisms at these inlets control the circulation patterns and hydrodynamics of the Middle Sound Estuary system. In this area, the tides are mixed and semi-diurnal. A month long study to measure directional currents and water levels within the estuary and adjoining inlets was conducted using an Acoustic Doppler Current Profiler (ADCP) and continuously recording YSI pressure gages at seven locations. Computations of tidal prism were performed to develop an understanding of the existing hydrodynamic system. Flood tidal prisms were computed at $23\text{x}10^6$ m^3 ($809\text{x}10^6$ ft$^{3)}$, $11\text{x}10^6$ m^3 (372)x10^6 ft^3, and $7\text{x}10^5$ m^3 ($25\text{x}10^6$ ft$^{3)}$ at Masonboro, Rich, and Mason Inlets, respectively, based on ADCP measurements taken on July 14, 1999. ADCP measurements taken biweekly during June and July 1999 confirm these relative values of tidal prism for the three inlets. Further, based upon prior studies by Jarrett (1976), the reported spring tidal prism at Masonboro Inlet was $24\text{x}10^6$ m^3 ($855\text{x}10^6$ ft^3) after construction of the north jetty.

Fig. 2. Mason Inlet (Dec 2001) prior to construction of inlet relocation project.

Both the Town of Wrightsville Beach and Figure Eight Island have undertaken inlet maintenance dredging for navigation and to provide material for beach nourishment. Due to extensive layers of rock along the North Carolina coast, very limited offshore sand sources are available and thus, nourishment projects commonly depend on inlet maintenance material as a sand source. Masonboro Inlet, at the southern end of Wrightsville Beach, is a federally maintained inlet that provides more than 460,000 m^3 (600,000 yd^3) of material to nourish Wrightsville Beach every 3 years. Similarly, at Figure Eight Island, the purpose of the dredging at Banks Channel and Rich Inlet has been to maintain navigation and to provide a source of sand for protection of the island's beaches. According to a study by Cleary (May, 1990), the southern shoreline of Figure Eight Island experienced a recession rate of 4.1 m/yr (13.6 ft/yr) between 1984 and 1989. Since 1990, the beaches immediately updrift of Mason Inlet have continued to experience chronic, high rates of erosion. As is typical of rapidly migrating or unstable inlet, Mason Inlet is absent a well-developed, ebb tidal shoal and experiences a strong downdrift movement of sand onto the inlet's updrift depositional planform, resulting in chronic erosion of the updrift beaches. For this reason, a goal in formulating a long-term solution to the migration of Mason Inlet was to address this chronic erosion problem. The native sand mean grain sizes at these beaches range from 0.22 to 0.25 mm, whereas channel maintenance material is typically finer, characterized by mean grain sizes of 0.18 to 0.22 mm.

The purpose of this paper is to review the project's history and the first year of observations of morphology and hydrodynamics following relocation of the Mason Inlet channel. Data are presented to examine ebb shoal development, inlet cross-section equilibration, beach response, and changes in the tidal prism and flow distribution through the primary two tidal channels connecting the new inlet with the AIWW following the inlet's relocation.

ALTERNATIVE ACTIONS TO AMELIORATE INLET MIGRATION

Several alternatives were examined and developed by the County acting as the local project sponsor for the primary stakeholder, the Mason Inlet Preservation Group. These alternatives included the "no-action" alternative which would demolish the hotel and relocate homes to allow the inlet to continue its expected southerly migration, "inlet closure" which assumed that the inlet would close naturally over a 3-to-5 year period following demolition of the hotel, and "inlet relocation" with 19 different configurations of the inlet relocation project. The no-action alternative would allow the continued southerly migration of Mason Inlet and subsequent destruction of private, public, and commercial property and any buildings remaining on that property at a 30-yr cost of $237 million (PWD).

A somewhat similar alternative, inlet closure, is based on the assumption that the inlet would ultimately close by natural processes aided by failed structures blocking the tidal flows, inlet channel shoaling, and a continuous reduction in tidal prism. There are many thousands of acres of coastal marsh and small tidal creeks surrounding this inlet that would be adversely influenced by this alternative. As a result, the County did not support inlet closure as an acceptable solution to the problem. The third alternative, inlet relocation, would close the existing Mason Inlet channel at its present location adjacent to Wrightsville Beach and reopen Mason Inlet 2,800 ft north. The benefits of inlet closure and relocation would prevent the future loss of property and tax revenue and eliminate adverse environmental effects of reduced flushing in the AIWW associated with the inlet closure and no-action alternative. Thus, the selected long-term solution to the problem was inlet relocation.

ORIGINAL INLET

Mason Inlet had a history of migration and change prior to 1997 when the inlet was temporarily stabilized. Although the inlet was relatively stable between 1963 and 1977, this was followed by a period when the inlet migrated south at rates of 48 to 210 ft/year between 1971 and 1996 (Fig. 3). Between 1996 and 1997, the inlet migrated at a higher rate of 0.4 m (1.1 ft) per day, with episodic erosion events occurring during the spring tides (Fig. 4).

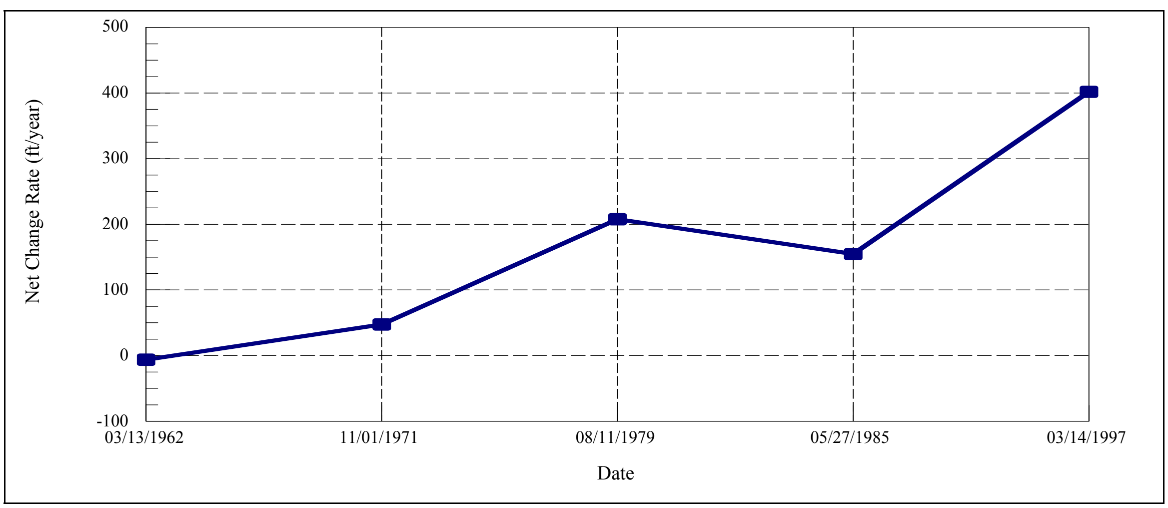

Fig. 3. Migration rate at Mason Inlet.

In recent years, land-falling hurricanes have caused major erosion on this North Carolina coastline with three hurricanes impacting the site in 1996 (Bertha, Fran, and David), and with

Hurricane Bonnie hitting this coast in 1998 and Floyd making landfall in 1999. These hurricanes caused both scour and deposition within Mason Inlet. The greatest factors entering these changes were the sand-rich beaches following nourishment in 1996, 1999 and 2002 and the height of the storm surge relative to the peak dune elevations (12 to 16 ft) at the inlet.

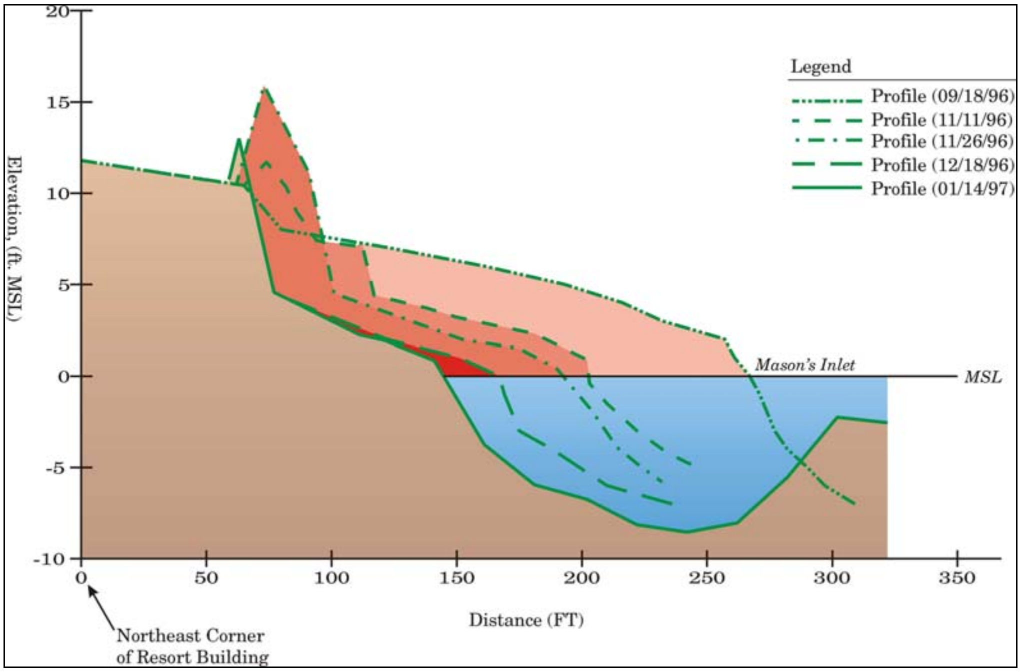

Fig. 4. Shoreline change at Mason Inlet's south channel bank (1996-1997)

Project Design and Engineering

The primary goals of the project were to design a reasonably stable natural inlet along a designated "inlet corridor," to minimize impacts to the hydrodynamic regime at adjacent inlets, minimize adverse impacts to bird habitat and marsh losses, and to restore the adjacent updrift beaches of Figure Eight Island. The primary components the project design called for relocating the inlet channel approximately 850 m (2,800 ft) north of its 2001 pre-project location. The inlet channel was dimensioned to insure equal or greater hydraulic capacity than expected based on flow predictions from a 2D hydrodynamic model of the three inlets and adjoining estuary system, the historic cross-sectional area of the inlet throat in 1996 and historical mean inlet widths and depths. The predicted stable cross-sectional area for a tidal prism of 52×10^6 m^3 (170 - 200×10^6 ft^3) indicated that an area of 465 m^2 (5,000 ft^2) was required. This computed cross-sectional area was close to the measured May 1996 cross-sectional area of the inlet's throat. To accomplish the inlet's relocation, the new inlet channel was to be excavated by extending the Mason Creek channel alignment across the sand spit peninsula that is the southern terminus of Figure Eight Island. An excavation volume of some 260,000 m^3 (340,000 yd^3) of medium grained to coarse sand was required to accomplish the design cross-section through the island.

Mason Creek, which was shoaled and essentially closed, was to be dredged to enhance the hydraulic flows between the AIWW and the new inlet channel and to reduce flushing times along the Middle Sound Estuary and the adjoining AIWW. The 18 acre sedimentation basin, or sand trap, situated at the ocean entrance to Mason Creek, with a holding capacity of 160,650 m^3 (210,000 yd^3) was designed to capture the sand that would form a flood tidal shoal and prevent

large flows of sand into the AIWW. The fill template for the original inlet covers some 24 acres and extends 518 m (1,700 ft) northward from the pre-project inlet south channel bank. The Project's final excavation plan would require removal of 110,925 m^3 (145,000 yd^3) of sand from Mason Creek, 256,275 m^3 (335,000 yd^3) from the sand trap and 260,100 m^3 (340,000 yd^3) from the new inlet channel. Excavation to construct the initial project would result in a net quantity of an estimated 612,000 m^3 (800,000 yd^3), with 206,550 m^3 (270,000 yd^3) placed to fill the original inlet channel and 382,500 m^3 (500,000 yd^3) for beach nourishment .

An inlet maintenance frequency of 3 years was projected including dredging the sand trap and an area contiguous with the north-channel bank of the inlet to situate the channel at the northern limit of the "inlet corridor." Maintenance dredged material would be placed either along the beaches of Figure Eight Island or further south along the north end of Wrightsville Beach based on the results of the beach and inlet survey monitoring plan. In the event that threshold sand losses exceed pre-established rates sand placement would occur along the affected area(s) of inlet impact. Mason Creek hydraulic efficiency and alignment with the new inlet channel are key elements in preventing high rates of inlet migration in future years. However, if the maintenance to prevent this migration proves too costly, the initial project would provide an estimated 10 years of protection prior to impacting development at the north end of Wrightsville Beach. The resulting benefit-to-cost ratio, under this outcome would exceed 3:1 and provide significant benefits and return on their investment under the worst-case situation.

Inlet Opening

Between January 2002 and April 15, 2002, the construction phase of the Mason Inlet Relocation Project was completed. Two cutter-head hydraulic dredges (14 and 16 inches) and several large capacity excavators worked concurrently to construct the project within the tight time frame allowable by the project's permits. Mason Creek channel, excavated to a design width of 140 ft and depth of 10 ft (NGVD) along a 1,400-m (4,580 ft) length, was dredged between the new inlet and the AIWW at the same time that a second dredge excavated the sedimentation basin, hydraulically moving sand 3 miles north onto the beaches of Figure Eight Island. Simultaneously, a truck haul operation moved sand from the new inlet channel excavation site on Figure Eight Island north to the beach nourishment site, placing sand onto the landward portion of the berm template, with hydraulic placement of material onto the seaward portion of the berm template. During the design and construction process a number of specific challenges were encountered to which engineering solutions were found. In particular, the sheet pile wall with geotextile containers to reinforce the tie-ins, proved to be a essential element of the construction design when a strong nor'easter hit the site one week prior to the planned opening of the new inlet nearly causing a near breach at the structure's terminus.

The new Mason Inlet channel was opened on March 7, 2002 during a neap tide phase with the temporary sheet pile removed just prior to the beginning of an ebb tidal cycle. The following day, the Mason Creek channel, plugged by a 60 m (200 ft) unexcavated section, left in place to prevent extreme currents during the initial inlet opening, was dredged. Initial tidal flows between Mason Creek and the AIWW exceeded 1.6 m/sec (5 ft/sec) and boats were advised to remain away from the area until the inlet channel stabilized. Within a week of the new inlet's opening, the outer ocean channel scoured to a depth of 1.5 m (5 ft), providing boaters an opportunity to use the inlet. An aerial photograph of the site taken one week after the inlet's opening (Fig. 5) shows the old and the new inlet channels. The original inlet channel was subsequently closed on March 14, 2002 when a bridge of sand was pushed from the sand

disposal site at the south end of Figure Eight Island across the narrowest section of the inlet throat. Sediment excavated from Mason Creek and placed within the 12 –acre, diked stockpile area, provided the primary source of material for the inlet infill operations. An additional 57,400 m^3 (75,000 yd^3) of sediment excavated from the sand trap was hydraulically placed along the oceanfront to construct a typical beach profile.

Fig. 5. Mason Inlet one week after inlet opening (photograph March 14, 2002).

Monitoring Plan

A comprehensive physical and biological monitoring program was formulated during the design and permitting phases of the Project (Table 1) to determine the post-construction shoreline changes, inlet maintenance dredging requirements, and water quality and environmental resource impacts,. The monitoring program, (refer to Table 1) was to be implemented by New Hanover County, North Carolina as an element of the Mason Inlet Management Plan (MIMP), to address the Project's potential impact to the adjacent island shoreline(s) position and the new inlet's maintenance dredging volumes and frequency. The MIMP also established threshold shoreline and beach losses that will trigger maintenance dredging and, or shoreline restoration events, and that could be performed under the authorization granted by the Federal Section 404 Permit. This Plan requires video monitoring, beach profile surveys, rectified aerial photographs, sand sampling, water quality sampling, biological transects, benthic sampling and migratory and protected shorebird monitoring.

To augment the County's studies, the U.S. Army Corps of Engineers' Coastal Inlets Research Program is supporting field studies to document development of the new ebb tidal shoal and to monitor circulation changes within the 3 affected tidal channels of the estuary (Fig. 6). These field investigations include periodic bathymetric surveys of the abandoned and new ebb-tidal shoals, and of the entrance and inlet channels; beach profile surveys; and measurement of current velocity and water surface elevation at three locations. Findings of these comprehensive monitoring studies will provide valuable data and information to guide future maintenance

decisions and advance knowledge and understanding of coastal inlet processes. In addition, the North Carolina Sea Grant program and the University of North Carolina at Wilmington are conducting field studies to document circulation changes within the surrounding estuary.

Table 1. Summary of the Monitoring Plan for the Mason Inlet Relocation Project

Task	Time in Years from Initial Surveys												
	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10
Beach Profiles													
Native Sand and Borrow Sand Quality													
Controlled Aerial Photography													
Plover and Water Bird Surveys													
Current and Water Level Measurements													
Protected Species Surveys													
Wetland Surveys/Characterization													
Benthic Macro-invertebrates													

Fig. 6. Major morphologic features and three instrument locations.

FIRST-YEAR RESPONSE

Hydrodynamics

Continuous water level and directional current measurements have been collected at the AIWW near Mason Creek and at the two tidal channels conveying tidal flows from the relocated Mason Inlet to the AIWW, since February 1, 2002 or approximately 1 month before the inlet was opened. Data recovery has been excellent overall, with shoaling in Banks Channel contributing to the periodic loss of current measurements since October 2002. Water level in Mason Creek,

Banks Channel and the AIWW are compared approximately 3 weeks after inlet opening during a spring tidal cycle. The ranges of water level were equivalent at 1.48 m at the Mason Creek and 1.52 m at the AIWW locations during this period of time, a 1-mi phase lag at the AIWW site was observed (Fig. 7). Currents within the reopened Mason Creek channel exceeded 1.5 m/sec (4.5 ft/sec) decreasing 6 months after the inlet's opening to a maximum a maximum of 0.5 to 0.7 m/sec (1.6 to 2. ft/sec) following initial equilibration of the channel cross-section occurring during the first 3 months (i.e., July 2002). October 2002 surveys show minor adjustment of the cross-section with maximum velocities remaining nearly equivalent based on observations of flow from June through December 2002 in Mason Creek. In contrast, Banks Channel has experienced a gradual reduction in velocities with significant shoaling along the southernmost 460 m (1,500 ft) inlet entrance section.

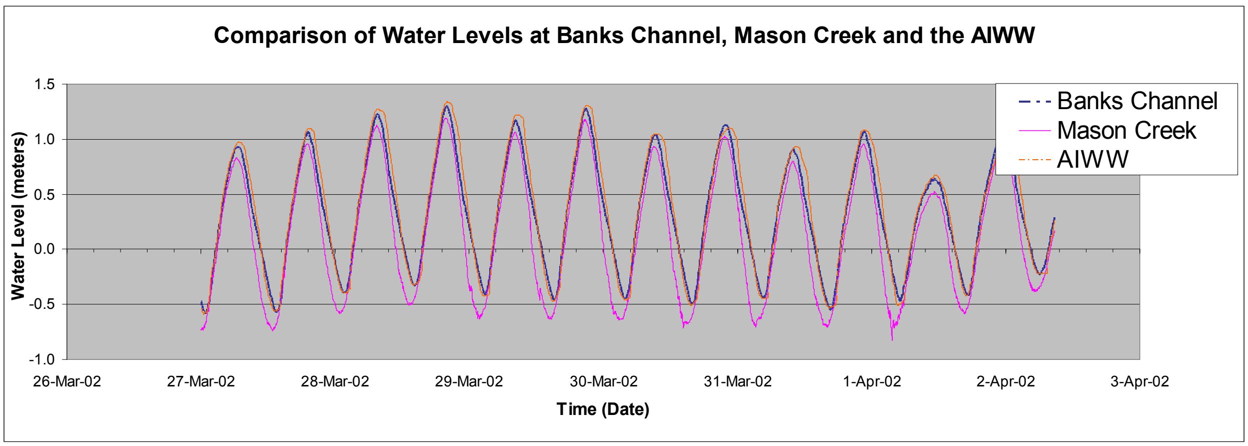

Fig. 7. Seven-day comparison of water levels during first spring tidal cycle after reopening of Mason Creek Channel and New Mason Inlet

In the design-development phase of this Project, calculations were made to predict changes in tidal dominance and tidal prism of Masonboro Inlet, Mason Inlet, and Rich Inlet expected from the construction of the new Mason Inlet and Mason Creek channels. The design tidal prisms at neap and spring tide were calculated by a 2D depth-averaged hydrodynamic model to be 52×10^6 m^3 (170 - 200×10^6 ft^3). The model results predicted that the tidal prism would increase 150 percent at Mason Inlet. At Masonboro and Rich Inlets, a slight reduction in tidal prism was expected to occur. Maximum tidal volumes predicted by the model for the 140-ft wide Mason Creek channel were expected to result in a tidal flow distribution of 40 percent through the newly dredged Mason Creek Channel and 60 percent through Banks Channel. Tidal prism calculations indicate that the tidal flow distribution was nearly equal (51:49 distribution between Mason Creek and Banks Channel) in April and May 2002 with tidal flows gradually shifting from Banks Channel to Mason Creek channel (65:35) from June through November 2002.

Computations of tidal prisms at the three monitoring locations were developed based on periodic surveys of the channel cross-sections, water level variations at 3- to 6-min intervals and the mean current velocity determined by the acoustic Doppler profilers every 3 min, and summed until the direction of flow reverses. Prior to construction of the project, tidal and current studies at Mason Inlet indicated that the inlet was flood dominant, and predicted to be flood dominant following reopening of the new inlet. Tidal prisms computed for Mason Creek and Banks Channel after project construction indicated that the inlet is flood dominant. Immediately upon the inlet and channel opening, a 3 to 6 percent greater flow occurred during a flood tidal

condition than observed during ebb tidal conditions. In October and November, flood dominance of this channel increased to 10 to 12 percent, which is the period of time when the sand trap began to fill and interior shoaling increased along the entrance section of Banks Channel. To stabilize the location of the inlet, a design goal was to maximize flow through the Mason Creek, while controlling the alignment of Mason Creek with the new inlet channel (Fig. 9). This goal has been reached in part, by the dominance of Mason Creek tidal prism when compared to the Banks Channel tidal prism, although the flood tidal flows are contributing to shoaling at the inlet entrance to Banks Channel and Mason Creek. The shoaling appears to be greatest along Banks Channel that has caused a reduction in the overall tidal prism through Banks Channel.

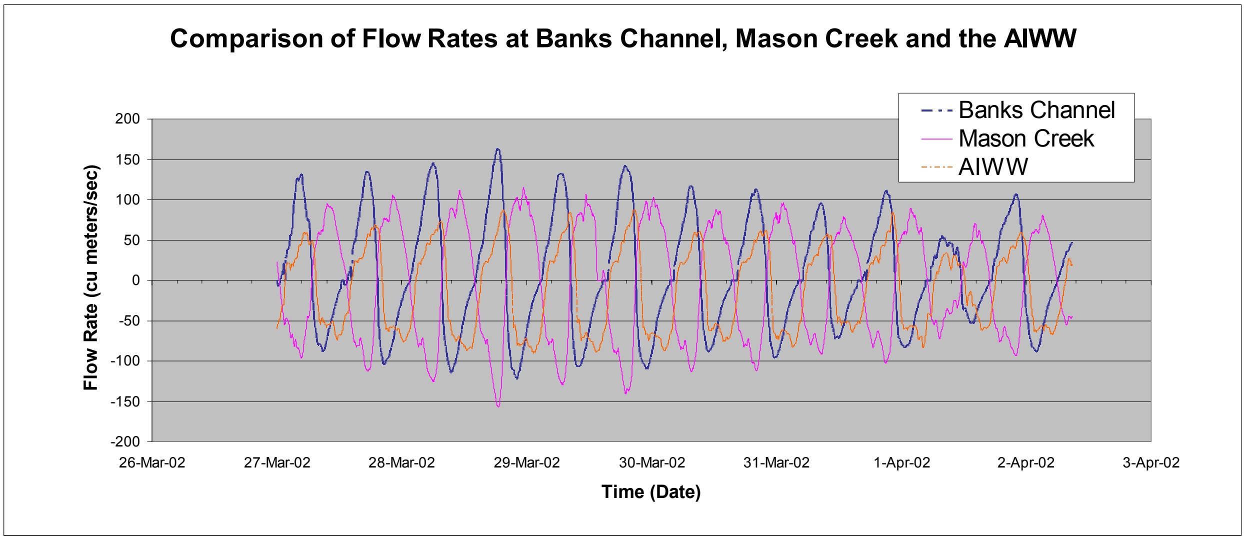

Fig. 8. Seven-day Comparison of Velocities 2 months after Reopening of Mason Creek Channel and New Mason Inlet (negative flow is west, or towards the AIWW)

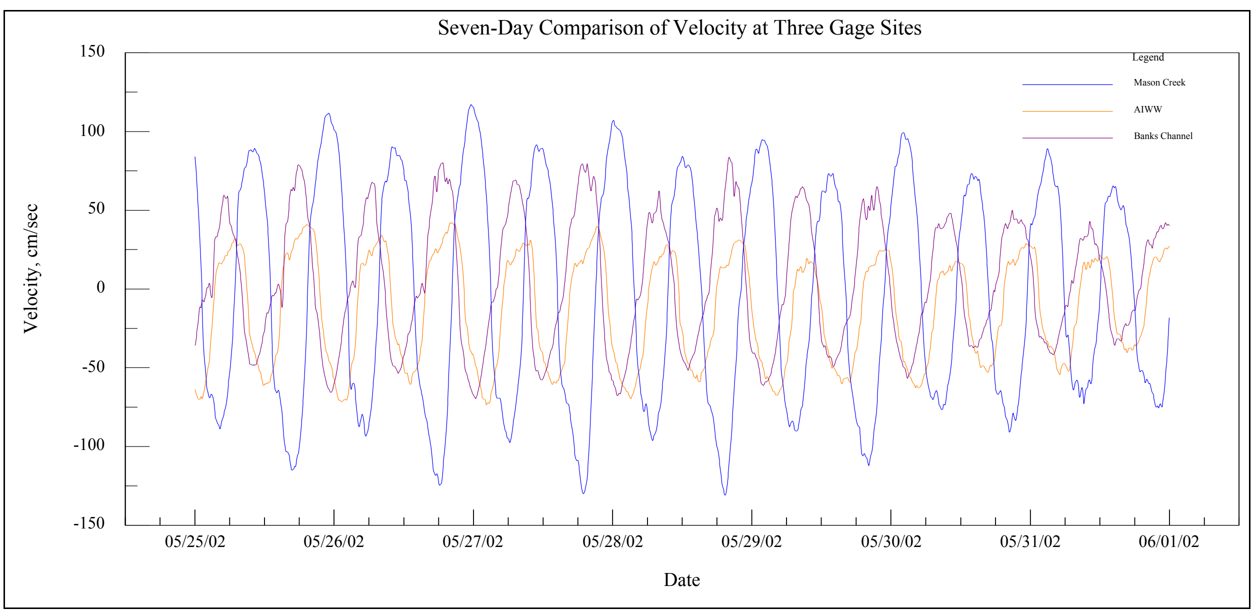

Fig. 9. Seven-day comparison of velocity after reopening Mason Creek (during spring tide)

Geomorphology

Ebb Shoal of Original Inlet. Soon after the original inlet was closed, the old ebb tidal shoal began to move onto the shoreline fronting the old inlet area. Subsequently, a long tidal pool formed as the seaward margin of the shoal attached to the downdrift shoreline and remained intact from June through October 2002. The newly formed tidal pool afforded beach users a wonderful place to play and swim, with many people visiting to enjoy the pool. By late November 2002, this sand body had been redistributed by waves and currents, shifting primarily north with no bulge or other evidence of the original ebb tidal shoal.

The collapse of the ebb shoal at the original inlet entrance is of theoretical interest and was captured quantitatively in monitoring surveys (Fig. 10). Assuming that the bathymetry did not change substantially from the December 2001 survey until closing of the original inlet in early March 2002, the October 2002 survey allows a 6-month post-closing estimate of volume change to be measured. In Fig. 10, the volume change within above the 1-m contour was 130,000 m^3, with most of this sand reaching shore soon after the closing to form the long tidal pool.

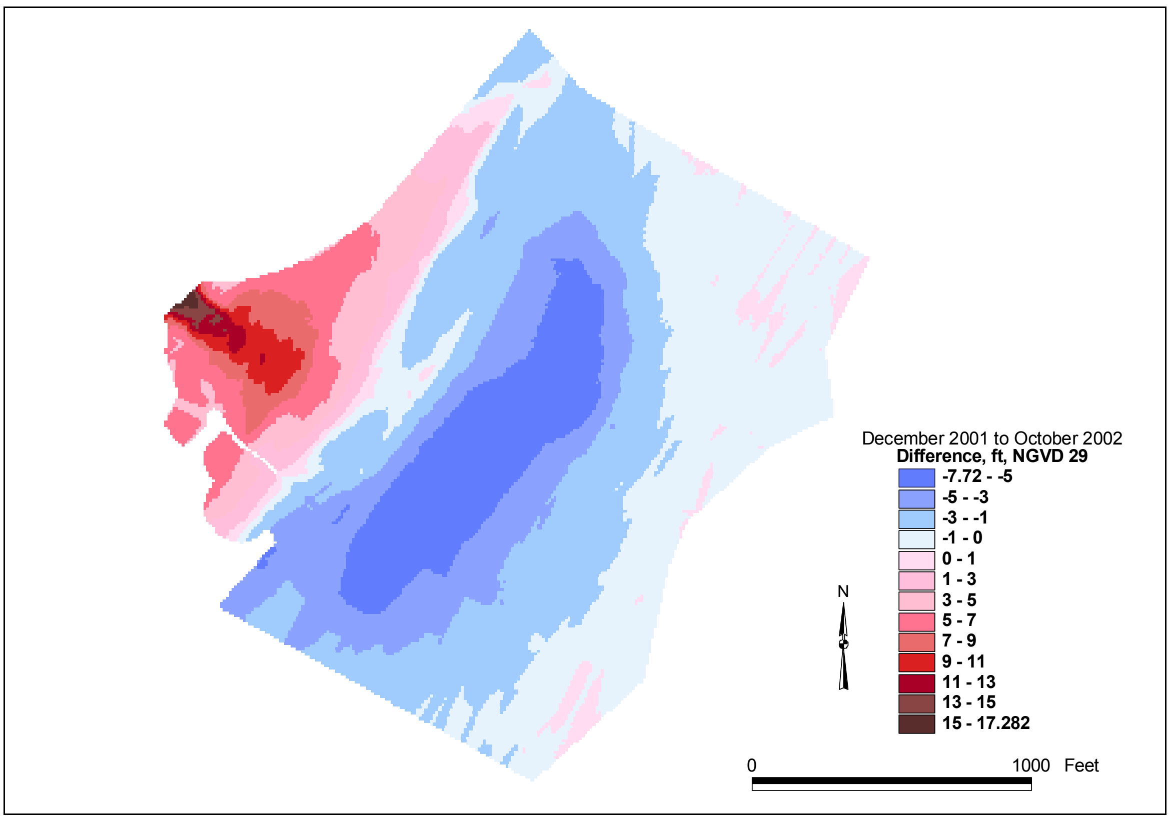

Fig. 10. Bathymetry change at original inlet, December 2001 to October 2002 (6 months post inlet closing).

Ebb Shoal of New Inlet. According to a predictive relation of Walton and Adams (1976), based on the calculated tidal prism the volume of the ebb shoal is expected to reach 0.9 to 1.2 x 10^6 m^3 (1.2 to 1.6x10^6 yd^3), at which time natural sand bypassing would be fully established. The monitoring program intends to capture growth of the ebb shoal. The 6-month post-inlet opening survey (difference shown in Fig. 11) gave a gain of 160,000 m^3 (212,000 yd^3) above the .03-m

contour and 180,000 m^3 above the zero contour. The ebb shoal was remarkably symmetric, suggesting balanced longshore sand transport or weak sand transporting capacity by waves for the 6-month period as compared to the tidal prism of the newly created inlet. It will be interesting to observe both the growth and symmetry of the ebb shoal at the new inlet.

The Reservoir model (Kraus 2000) was run with an equilibrium volume of the ebb shoal as 1.2×10^6 m^3 and with a representative gross longshore transport rate of 500,000 m^3/year, based on information from several sources. The model well reproduced the 6-month volume as found above and predicts the ebb shoal will approach a volume of 1 million cubic meters within 5 years, at which time natural bypassing is predicted to be 80 percent.

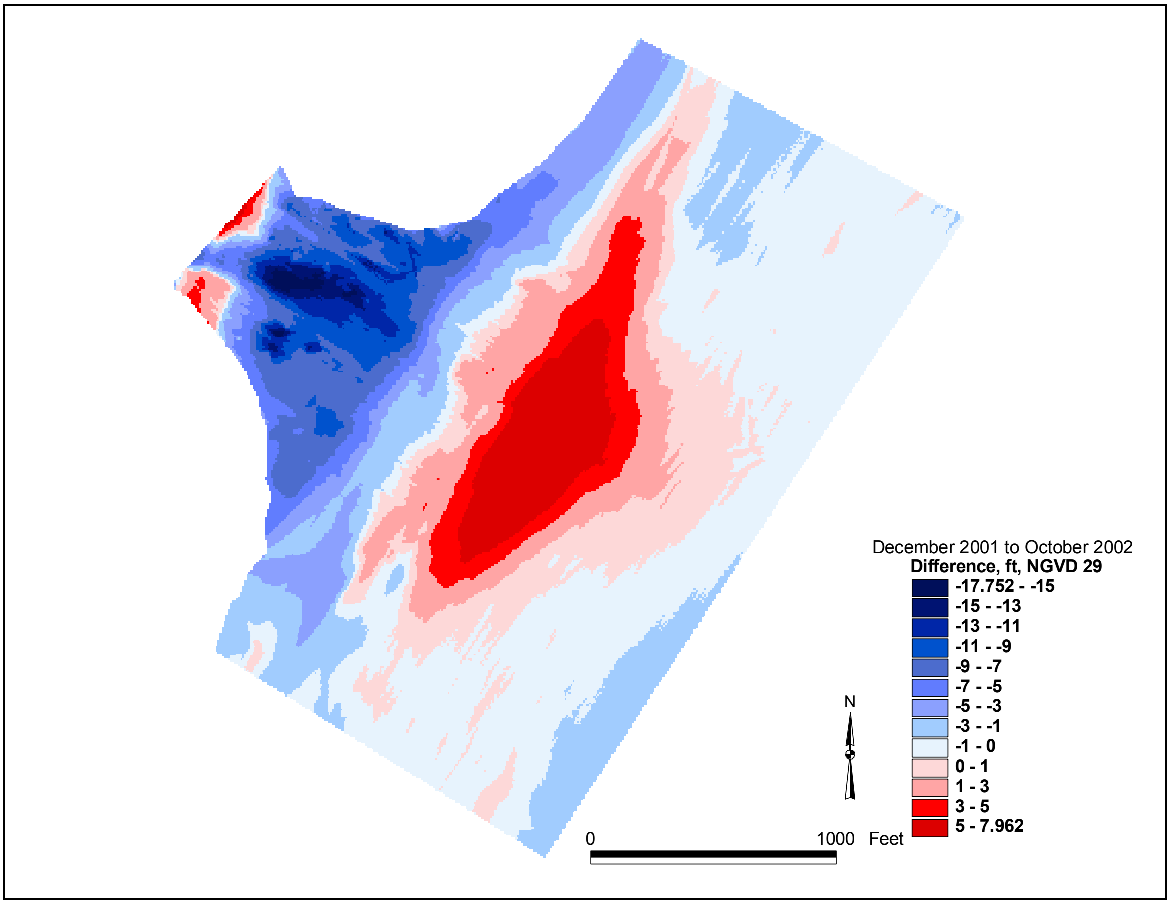

Fig. 11. Bathymetry change at new inlet, December 2001 to October 2002 (6 months post inlet opening).

CONCLUSIONS

The inlet relocation project at Mason Inlet and the reopening of Mason Creek has resulted in creation of a new and more stable inlet channel with increased tidal prism and flushing within the Middle Sound Estuary. Inlet relocation and closure of the original inlet have prevented the loss of commercial and residential property, roads, and utilities that were imminently threatened by the inlet's migration. Substantial information and data are been gathered on this unique project with significant scientific and engineering knowledge to be gained on inlet dynamics.

Results from the first year following inlet relocation have shown a shift in tidal flows from Banks Channel to Mason Creek, with the new inlet acting as a sand trap due to the flood-dominant tidal flows. The location of the inlet has been relatively stable with a small shift of the channel centerline toward Wrightsville Beach. An increase in ebb flow through Mason Creek would be expected to reduce interior shoaling and reduce southerly inlet migration. The design channel geometries at Banks Channel and Mason Inlet should consider the information gathered in this study in preparing for construction of the first inlet maintenance event. The tidal prism is significantly greater in Mason Creek than through Banks Channel that, in concert with the predominant flood over ebb tidal flows, contributes to shoaling rates observed at the inlet entrance to Banks Channel and Mason Creek. Shoaling appears to have been greatest along the southern 350 m of Banks Channel. resulting in a reduction in the overall tidal prism through this channel.

The abandoned ebb shoal at the original inlet quickly collapsed and moved onshore. The ebb shoal at the relocated inlet is presently symmetrical and growing rapidly. Within 5 years, the ebb shoal is predicted to be at 90% equilibrium volume, and natural sand bypassing will be nearly fully established.

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